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13. ABSTRACT (Maximum 200 words) This research was aimed at developing an improved understanding of hypersonic exothermic flows through the application of modern experimental methods and finite-rate-chemistry flowfield modeling. The emphasis has been on providing fundamental data, of flowfield structure and combustion ignition times, which are relevant to the ongoing development of the ram accelerator concept. Work in flow imaging and modeling utilized the Stanford expansion tube with a combined OH PLIF and schlieren imaging technique. This approach was successfully applied to the study of unsteady combustion in blunt body flows, oblique detonations in wedge flows, and simulated ram accelerator flows. In parallel, combustion ignition times of ram accelerator propellant mixtures were measured in the Stanford high pressure shock tube. These data have yielded improved kinetic models of ram accelerator ignition chemistry. Future work will be concentrated in combining analytical and numerical modeling with the imaging experiments, and in developing reduced-size kinetic mechanisms of ram accelerator combustion chemistry. DTIC QUALITY INSPECTED 2				
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SHOCK TUBE STUDIES OF RAM ACCELERATOR PHENOMENA

**FINAL PROGRESS REPORT
FOR THE PERIOD
1 APRIL 1994 - 1 SEPTEMBER 1997**

U.S. ARMY RESEARCH OFFICE

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SUBMITTED BY R. K. HANSON

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1) STATEMENT OF THE PROBLEM STUDIED

The ram accelerator is a novel propulsion strategy pioneered in the late 1980s by researchers at the University of Washington (UW). In a ram accelerator, a projectile is fired at supersonic velocity into a tube filled with a premixed gaseous propellant mixture. A structure of shock waves forms around the projectile which increases the pressure and temperature sufficiently to ignite the gas mixture. The energy release from combustion provides thrust which continuously accelerates the projectile down the length of the tube. The UW research group has successfully built and tested a 37-mm ram accelerator in their laboratory. In recent years, the US Army has also built a 120-mm ram accelerator at the ARL at Aberdeen Proving Ground.

A major problem in ram accelerator research is the lack of detailed understanding of the actual flow physics and chemistry around the projectile. Work at Stanford has been aimed at developing an improved understanding of high-speed exothermic gas flows through the application of modern experimental methods and finite-rate-chemistry flowfield modeling. Thus far, the emphasis has been on providing fundamental data of flowfield structure and combustion ignition times. The data are particularly useful for improving the accuracy of the computational codes which support ram accelerator development.

2) SUMMARY OF THE MOST IMPORTANT RESULTS

This program began formally on 4/1/94. Primary activities are highlighted below.

Imaging and Modeling of Hypervelocity Exothermic Flows

During 1994, our primary activity was the design and construction of a new expansion tube facility. An expansion tube is essentially a high-velocity, short-duration wind tunnel similar to a conventional shock tube. A model simulating relevant aspects of ram accelerator flows is mounted at the exit of the tube. This approach allows for the application of spatially and temporally resolved imaging diagnostics to study the flowfield physics and chemistry around the model. The Stanford expansion tube has successfully accelerated hydrogen-, methane- and ethylene-based fuels to velocities ranging from 1700-2200 m/s (Mach 4-7). Work in the following year (1995) was concentrated both on characterizing the expansion tube and performing initial PLIF (NO, OH, and acetone) imaging experiments of blunt body and wedge flows. A combination of pitot pressure, IR absorption, and NO PLIF thermometry and shock wave angle measurements was employed to determine the free-stream flow conditions at the exit of the tube. The results compared well with viscous shock tube theory, and form the database critically needed for accurate modeling of high-speed reactive flows.

A significant accomplishment in the final year (4/96-4/97) was the development of a simultaneous OH PLIF and schlieren imaging technique. This is the first time these complementary techniques have been applied simultaneously, and enables detailed study of both gas dynamic effects and reaction fronts. The simultaneous technique was applied to study hypervelocity reactive flows around blunted (both hemispherical and flat-faced) cylinders. Both steady and unsteady combustion flows have been observed, with research emphasis on the latter

case due to relevance to subdetonative ram-accelerator propulsion. In addition, a pressure transducer installed in the forebody of the model provided the first direct measurements of pressure oscillations in the unsteady flows. Ongoing modeling work is aimed at correlating the strength and frequency of the oscillations with the body diameter and curvature, and mixture ignition and heat release properties.

Simultaneous OH PLIF and schlieren imaging was also applied to study shock-induced combustion and oblique detonation wave formation in 2-D wedge flows. Oblique detonations, which occur in the limit of fast ignition behind an oblique shock, are a phenomenon of significant importance to superdetonative ram-accelerator propulsion. Experimental work in the last year employed a 40° (half-angle) wedge body, while varying the gas mixture composition and pressure to alter the ignition delay and energy release. Analysis was focused on the transition to detonation and resultant wave angle through Rankine-Hugoniot shock-polar methods and finite-rate kinetic modeling. An additional set of experiments was also performed studying the confined flow between two wedges. This work investigated ignition through shock-reflection and viscous flow phenomena, issues which are critically important in actual ram accelerator flows.

In an effort to develop an in-house numerical modeling capability for comparison with the experimental results, an inviscid flow, finite-rate chemistry CFD code was developed and tested by Dr. Toshimitsu of Kyushu University during his visit to our laboratory. This code was developed from a code originally written by Dr. A. Matsuo, now at Keio University and previously a doctoral student with Prof. Fujiwara at Nagoya University. To summarize, both reactive and nonreactive simulations of experimental results yielded good agreement with the data. Supercomputer access for the reactive test cases was provided by Dr. Nusca at ARL.

Measurements and Modeling of High-Pressure Ignition Kinetics

In a parallel effort, conducted in a high-pressure shock tube, reaction kinetics experiments were performed in support of the ARL ram accelerator effort at Aberdeen. This helium-driven, double-diaphragm shock tube can access pressures as high as 800 atm behind the reflected shock wave, where optical diagnostic techniques are used to measure combustion species of interest. In these tests, ignition delay time measurements were performed for mixtures of direct interest to ARL. Prior to these measurements, no data existed at conditions representative of the ram accelerator (i.e., pre-ignition pressures greater than 50 atm, temperatures less than 1400 K, and fuel-rich CH_4 mixtures with less than 70% diluent gas). Ignition chemistry is important in the design of the ram accelerator to prevent premature combustion near the projectile forebody, and ignition delay time measurements provide the necessary data to extend detailed kinetics models into the appropriate operating region of interest. Such fundamental data are relevant not only to the ram accelerator, but also to the general development of finite-rate-chemistry models for detonation and ballistics studies as well.

Major accomplishments in the kinetics program have been both experimental and analytical in nature. For example, ignition delay times for a number of methane-based mixtures of importance to the ARL ram accelerator program were measured; the combination of test

conditions (up to 260 atm) and mixtures has provided a range of empirical correlations that completely characterize the expected range of ARL methane-based ram accelerator mixtures. To improve agreement between detailed kinetics models and the experimental data, a state-of-the-art, 175-reaction methane mechanism was improved by adding reactions and species of importance at the higher-pressure, lower-temperature, fuel-rich conditions where ram accelerator ignition may occur. Good agreement was obtained between the updated model and the experimental data, particularly at lower temperatures and higher pressures, where the original mechanism does a poor job of predicting ignition delay time.

3) LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS

M. Kamel, C. I. Morris, M. C. Thurber, S. D. Wehe, and R. K. Hanson, "New Expansion Tube Facility for the Investigation of Hypersonic Reactive Flow," Paper No. 95-0233 at the 33rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 9-12, 1995.

C. I. Morris, M. R. Kamel, M. C. Thurber, S. D. Wehe, and R. K. Hanson, "Development of an Expansion Tube for Investigation of Combustion in Supersonic Projectile Flowfields," Paper No. 95-2717 at the 31st Joint Propulsion Conference and Exhibit, Lake Buena Vista, FL, July 10-12, 1996.

C. I. Morris, M. R. Kamel, M. C. Thurber, S. D. Wehe, and R. K. Hanson, "Development of an Expansion Tube for Investigation of Combustion in Supersonic Projectile Flowfields," presented at RAMAC II, 2nd Int. Meeting on Ram Accelerators, Seattle, July 17-20, 1995.

M. R. Kamel, C. I. Morris, M. C. Thurber, S. D. Wehe, and R. K. Hanson, "Use of an Expansion Tube for Imaging Studies of Hypersonic Reactive Flows Around Blunt Bodies," Proceedings of 20th Int. Symposium on Shock Waves, World Scientific, pp. 275-280 (1995).

M. R. Kamel, C. I. Morris, I. Stouklov and R. K. Hanson, "Imaging of Hypersonic Reactive Flow around Cylinders and Wedges," WSS/CI paper 95F-196, Stanford, CA, Oct. 30-31, 1995.

C. I. Morris, M. R. Kamel, I. G. Stouklov, and R. K. Hanson, "PLIF Imaging of Supersonic Reactive Flows Around Projectiles in an Expansion Tube," Paper 96-0855 at the 34th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 16-20, 1996.

A. F. P. Houwing, M. R. Kamel, C. I. Morris, S. D. Wehe, R. R. Boyce, M. C. Thurber, and R. K. Hanson, "PLIF Imaging and Thermometry of NO/N₂ Shock Layer Flows in an Expansion Tube," Paper 96-0537 at the 34th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, January 16-20, 1996.

C. I. Morris, M. R. Kamel, and R. K. Hanson, "Expansion Tube Investigation of Ram-Accelerator Projectile Flowfields," Paper 96-2680 at the 32nd Joint Propulsion Conference and Exhibit, Lake Buena Vista, FL, July 1-3, 1996.

E. L. Petersen, D. F. Davidson and R. K. Hanson, "Ignition Delay Times of Ram Accelerator Fuel-Oxidizer Mixtures," Paper AIAA-96-2681 at the 32nd AIAA Joint Prop. Conf., Lake Buena Vista, FL, July 1996, submitted to *J. Propulsion and Power*.

M. R. Kamel, C. I. Morris, I. G. Stouklov and R. K. Hanson, "PLIF Imaging of Hypersonic Reacting Flow Around Blunt Bodies," 26th *Symposium (International) on Combustion*, The Combustion Institute, pp. 2909-2915 (1996).

E. L. Petersen, M. Röhrig, R. K. Hanson and C. T. Bowman, "High-Pressure Methane Oxidation Behind Reflected Shock Waves," 26th *Symposium (International) on Combustion*, The Combustion Institute, pp. 799-806 (1996).

C. I. Morris, M. R. Kamel, and R. K. Hanson, "Investigation of Ram-Accelerator Projectile Flowfields in an Expansion Tube," 1996 JANNAF Combustion Subcommittee Meeting, Vol. I, 1997, pp. 383-393.

E. L. Petersen, D. F. Davidson, and R. K. Hanson, "Ram Accelerator Mixture Chemistry: Kinetics Modeling and Ignition Measurements," 1996 JANNAF Combustion Subcommittee Meeting, Vol. I, 1997, pp. 395-407.

M. R. Kamel, C. I. Morris, and R. K. Hanson, "Simultaneous PLIF and Schlieren Imaging of Hypersonic Reactive Flows Around Blunted Cylinders," paper 97-0913 at the AIAA 35th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6-9, 1997.

E. L. Petersen, D. F. Davidson and R. K. Hanson, "Kinetics Modeling of Shock-Induced Ignition in Low-Dilution CH_4/O_2 mixtures at High Pressures and Intermediate Temperatures," WSS/CI paper 97S-066, Sandia Nat. Labs., Livermore, CA, April 14-15, 1997.

E. L. Petersen, D. F. Davidson and R. K. Hanson, "Reduced Kinetics Mechanisms for Ram Accelerator Combustion," Paper 97-2892 at the 33rd Joint Propulsion Conference and Exhibit, Seattle WA, July 6-9, 1997.

A. Ben-Yakar, M. R. Kamel, C. I. Morris and R. K. Hanson, "Experimental Investigation of H_2 Transverse Jet Combustion in Hypervelocity Flows," Paper 97-3019 at the 33rd Joint Propulsion Conference and Exhibit, Seattle WA, July 6-9, 1997.

M. R. Kamel, C. I. Morris, A. Ben-Yakar and R. K. Hanson, "Experimental Investigation of Hypersonic Reactive Flows Around Axisymmetric Blunt Bodies," Paper 97-3177 at the 33rd Joint Propulsion Conference and Exhibit, Seattle WA, July 6-9, 1997.

M. R. Kamel, C. I. Morris, A. Ben-Yakar, E. L. Petersen and R. K. Hanson, "Experimental Investigation of Ram-Accelerator Flow Fields and Combustion Kinetics," presented at RAMAC III, 3rd Int. Meeting on Ram Accelerators, Sendai, Japan, July 16-18, 1997.

C. I. Morris, M. R. Kamel and R. K. Hanson, "PLIF and Schlieren Imaging of Oblique Detonation Waves," presented at the 21st Int. Symposium on Shock Waves, Great Keppel Island, Australia, July 20-25, 1997.

**4) LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY
ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT**

Graduate Research Assistants: Michel Kamel, Christopher Morris, Eric Petersen

Honors: Professor Hanson was elected to AIAA Fellow

Degrees Awarded: None

5) REPORT OF INVENTIONS

None